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SUMMARY

Three rocket thrust chambers with copper liners and thrust levels of 20.9 kilonewtons (4700 lbf) were cyclically test fired to failure. The combustion-chamber pressure was 4.14 MN/m^2 (600 psia) and the oxidant-fuel ratio of the liquid-oxygen and gaseous-hydrogen propellants was 6.0. Two of the liners were made from oxygen-free, high-conductivity (OFHC) copper and one from annealed Amzirc, which is a 0.15-percent-zirconium copper alloy. The liners were fabricated in the shape of a typical thrust chamber and contained externally milled slots for the coolant channels. The coolant channels were closed out by electroforming a 0.762-millimeter- (0.030-in.-) thick copper closeout over the channels to prevent leakage of the liquid-hydrogen coolant. A fiberglass composite was wrapped over the closeout to provide hoop strength only. A preliminary analysis was performed before fabrication to evaluate the theory that a thrust chamber with a compliant, fiberglass-wrapped copper closeout would have a longer cyclic life than one with a stiffer nickel closeout only. The analysis indicated that fiberglass-wrapped copper closeouts have the potential for increasing the life of thrust-chamber liners. The limited amount of experimental data showed that liner life was improved but that coolant leaks through the closeout could be a problem. The average experimental cyclic lives of the OFHC copper liners with fiberglass-wrapped copper closeouts were approximately 30 percent longer than the average life of identical liners that were tested under the same conditions but with electroformed nickel closeouts only. The chamber with the annealed Amzirc liner and the fiberglass-wrapped copper closeout was cyclically tested for 256 cycles before coolant leakage through cracks in the copper closeout became a hazard and required termination of the testing. This number of cycles was considerably more than the 63 cycles endured by the Amzirc liner in a comparable chamber with an electroformed nickel closeout only.

INTRODUCTION

Now that more emphasis has been placed on economy in research within NASA, the need for reusability has become apparent. Reusability, which has not been a major consideration in the past, has introduced many new design requirements for rocket thrust chambers. One of these is longer cyclic life. Large cost savings can be achieved for propulsion systems being used in the space shuttle and those being developed for use in vehicles such as the orbit transfer vehicle (OTV) by developing thrust chambers that can withstand numerous thermal cycles without failure.

The space shuttle main engine (SSME) operates at a chamber pressure of 20.7 MN/m^2 (3000 psia) and has a throat heat flux of 131 to 147 MN/m^2 (80 to 90 $Btu/in^2 \cdot sec$) and a life requirement of 55 thermal cycles. Thrust chambers for the OTV may have life requirements of over 200 thermal cycles. Achieving long thrust-chamber cyclic life at high chamber pressure and high heat flux is a difficult task.

In 1973, low-cycle fatigue was observed in a milled-channel thrust chamber fabricated from copper (refs. 1 and 2). Hannum, et al. (ref. 3) extended the data base by attempting to correlate the experimental lives of several thrust chambers with analytical predictions that used material fatigue data taken under uniaxial load and isothermal test conditions. For the most part these correlations were unsuccessful; however, a better understanding of the complexity of thrust-chamber failure mechanisms evolved. These studies, along with work reported by Quentmeyer (ref. 4), have led to a better characterization of failure mechanisms and the influence of alloy type, heat-flux levels, etc., on thrust-chamber life.

This experimental investigation of the effect of a fiberglass-wrapped copper closeout on thrust-chamber life is consistent with the overall goal of obtaining a better understanding of thrust-chamber cyclic life. Preliminary analytical studies indicated that thin copper closeouts with low-stiffness overwraps can improve the cyclic life of regeneratively cooled, milled-channel thrust chambers. This improvement in cyclic life was attributed to the theory that a thin closeout with a fiberglass overwrap would be less constrictive to the thermal growth of the liner during the firing cycle and thereby reduce the effective strain range. Therefore an experimental program was begun to verify that low-stiffness, fiberglass-wrapped closeouts give longer liner cyclic life than stiffer completely metallic closeouts.

PRELIMINARY ANALYSIS

Analytical Method

The conventional analytical approach to life prediction of regeneratively cooled, milled-channel thrust chambers with bonded metallic closeouts, such as the one shown in figure 1, includes a computer thermal analysis and a structural analysis of the throat section. The throat section is normally chosen because the high heat flux that occurs there generally produces the maximum strain. Temperatures obtained from the thermal analyzer program are input to the structural analysis program as loading conditions, along with the thrust load and the coolant and combustion-gas pressure loads. Output from the structural analysis in the form of strain ranges is used to enter laboratory-generated isothermal life curves that relate strain range with cycles to failure for the liner material.

Experimental thrust-chamber life tests, however, have shown that conventional low-cycle-fatigue life prediction methods do not necessarily apply to thrust-chamber life prediction (refs. 3 and 4). Results of these tests indicated that a reasonably accurate prediction must account for the coolant-channel geometry change that results from coolant-channel-wall thinning and bulging. Development of such a method is in progress but was not completed at the time of this analysis. Consequently the conventional method had to be used for the preliminary analysis. Although the accuracy of this method for predicting actual chamber life is questionable, it was felt that it is adequate for a preliminary investigation of the life-extending capability of fiberglass-wrapped closeouts.

The thermal maps required for the structural analysis are generated with a thermal analyzer computer program such as SINDA (ref. 5), which provides temperatures as a function of time. The most significant times for a rocket thrust chamber are those that correspond to the greatest temperature difference between the hot-gas-side surface and the closeout outer surface during the heating and cooling portions of the firing cycle. Generally this is when the maximum compressive and tensile strains occur. During the heating transient the thermal growth of the hot liner is restricted by the cooler closeout, so large plastic compressive strains are induced in the liner. A similar situation exists during the cooling transient except that the closeout is then at a higher temperature than the liner and thus tensile strains are induced in the liner.

Analyses of thrust chambers with stiff metallic closeouts show that the thermal tensile strain that occurs during the cooling transient has an effect on the total strain range. For chambers with fiberglass-wrapped closeouts, no bond exists between the thin closeout and the overwrap, so the closeout and the liner can shrink away from the overwrap during the cooling transient. Therefore, since the closeout is considerably thinner when wrapped with fiberglass and hence less stiff, the thermal tensile strains are small and can be neglected. The compressive thermal strain that occurs during the heating transient is the major contributor to the strain range.

It was assumed in the life analysis for fiberglass-wrapped closeouts that the closeout was not bonded to the overwrap. Consequently the assumption was made in the thermal analysis that the thermal resistance across the interface between the closeout and the overwrap was sufficient to allow the overwrap to remain near room temperature throughout the firing cycle. The SINDA computer program was used to generate the cross-sectional wall temperature profile.

The model that was developed to perform the thermal analysis is shown in figure 2. Because of symmetry, only one-half of a coolant-channel-wall cross section was required for the thermal model. The representative cross section was divided into 74 elements with a temperature node at the center of each element. Surface nodes were also specified on each element along the model boundaries, but they are not shown in the figure.

Data from the thermal analysis were used to define the thermal loading in the form of temperatures applied to the appropriate elements of the plane-strain structural model shown in figure 3. This model represented a section taken from the throat region of the thrust chamber, where the thermal loading was most severe. Because of symmetry, only one-half of a coolant-channel-wall cross section was required for the structural model, as was the case for the thermal model. Nodal forces were applied to the nodes of the elements bordering the coolant channel and those adjacent to the hot-gas-side surface to represent the coolant and hot-gas pressures, respectively. Input data used to characterize the temperature-dependent metallic material properties were developed from the data of references 6 and 7. Properties of wrought OFHC copper were used for the liner from the hot-gas surface to the outer surface of the coolant-channel ribs. Properties of electroformed copper were used for the thin coolant-channel closeout. The fiberglass overwrap was treated as an isotropic material with the typical mechanical and physical properties of a fiberglass-epoxy composite. The elastic modulus of the fiberglass overwrap was varied to study the effects of its stiffness on liner life. Obviously the anistropic properties of the fiberglass overwrap should be accounted for, but the RETSCP finite-element structural program (ref. 8) that was used for the analysis did not have that capability. It was assumed that the fiberglass overwrap was not bonded to the closeout.

Results of Structural Analysis

The effect on cyclic, effective strain range when just the fiberglass-overwrap stiffness is varied is shown in figure 4. (The elastic moduli of the liner and its closeout were constant.) Two curves are shown. One curve is the variation in maximum effective strain range, and the other is the variation in the average effective strain range of all the elements that are included in the 0.89-millimeter- (0.035-in.-) thick coolant-channel wall (elements 1 to 3, 6 to 8, 11 to 13, and 16 to 18 in fig. 3). The maximum effective strain range occurred in element 5 (fig. 3), which is on the hot-gas-side surface and at the centerline of the coolant-channel rib. Although the maximum effective strain range occurred in element 5, it seemed more reasonable to assume that fracture would occur in the thin coolant-channel wall. This failure mode is even more likely if any measurable change in geometry (such as thinout and bulging under pressure) occurs as a result of plastic flow during cyclic testing. Therefore it was felt that the chamber life would more nearly correspond to the value predicted by the average effective strain range.

As shown in figure 4, the effective strain range began to decrease considerably below a fiberglass-overwrap stiffness of approximately 2.6×10^8 N/m (1.5×10^6 lbf/in). It was estimated that the stiffness would range from 1.0×10^8 to 1.6×10^8 N/m (0.6×10^6 to

0.9×10^6 lbf/in). Thus at a mean value of 1.3×10^8 N/m (0.75×10^6 lbf/in) the maximum effective strain range would be 2.5 percent and the average effective strain range 2.3 percent. Also shown in this figure are the theoretical effective maximum and average strain ranges for a thrust chamber with a stiff electroformed nickel closeout. The maximum effective strain range for this chamber would be 2.85 percent and the average value 2.5 percent. For these effective strain ranges and the OFHC copper life curve from reference 6 and shown in figure 5, the minimum lives for a chamber with a fiberglass-wrapped copper closeout and a chamber with a completely nickel closeout are 80 and 60 cycles, respectively; and the lives based on the average effective strain range are 100 and 80 cycles, respectively. It was concluded then that a 25 to 30 percent improvement in life could be expected from a thrust chamber with a fiberglass-wrapped copper closeout that has a overwrap stiffness of 1.3×10^8 N/m (0.75×10^6 lbf/in).

The life curve for annealed Amzirc from reference 6 is also shown in figure 5. According to the analysis of reference 3, the theoretical strain ranges for the annealed Amzirc and the OFHC copper liners were approximately the same for chambers with nickel closeouts and the same temperature profiles (2.91 and 2.85 percent maximum and 2.56 and 2.54 percent average). Therefore, if it is assumed that this is also the case for chambers with fiberglass-wrapped copper closeouts, the minimum life from figure 5 for an annealed Amzirc liner with a fiberglass-wrapped copper closeout (based on a maximum strain range of 2.5 percent) would be 500 cycles, and the life based on an average strain range of 2.3 percent would be 700 cycles. The minimum life and the life based on the average strain range for an annealed Amzirc liner with a nickel closeout were approximately 330 and 500 cycles, respectively. Hence a life improvement of 40 to 50 percent, over that with a nickel closeout, can be expected for an annealed Amzirc liner with a fiberglass-wrapped copper closeout.

The theoretical life, in number of cycles, of the OFHC copper liner as a function of the fiberglass-overwrap stiffness is shown in figure 6, which combines figures 4 and 5. Two curves are shown again. Life increased rapidly below a stiffness of 1.8×10^8 N/m (1×10^6 lbf/in) and reached a maximum of 200 cycles at a stiffness of zero for the average effective strain-range curve. This is the predicted life for the limiting case, in which it was assumed that there was no fiberglass overwrap and that only the electroformed copper closeout resisted the pressure loads. Addition of a fiberglass overwrap, of course, adds strength to resist the pressure loads but shortens the life. Consequently, a fiberglass overwrap of the lowest stiffness that will contain the pressure loads is desirable for maximum life. However, an additional structure would be required to carry the thrust and gimbal loads across the thrust-chamber throat.

EXPERIMENTAL LIFE-TEST APPARATUS

Test Facility

The experimental portion of this investigation was conducted at the Lewis Research Center rocket-engine test facility. This is a 222 410-newton (50 000-lbf) sea-level rocket test stand equipped with an exhaust-gas muffler and scrubber. The facility used pressurized propellant-storage tanks to supply liquid oxygen and ambient-temperature gaseous hydrogen to the combustor. Liquid hydrogen was used as a coolant.

Details of the installation are shown in figure 7. Figure 7(a) shows the thrust stand and the exhaust-gas-scrubber entrance with a typical combustion chamber mounted in place. Figure 7(b) is a schematic of the test facility and shows the propellant supply and the instrumentation locations. The coolant flow loop was independent of engine propellant flow, and the spent hydrogen coolant was disposed of through a burn stack. For test convenience an external igniter torch was used to ignite the propellants. At ignition the flame front would pass upward through the throat and ignite the propellants in the combustion chamber.

A perforated manifold was installed at the nozzle exit plane as a facility safety precaution to flush the outside surface on the combustion chamber with helium in case hydrogen coolant leaked through the thin, electroformed copper closeout. (This manifold is not shown in fig. 7.)

Data Recording

All pressures and temperatures were recorded in digital form on a magnetic tape for entry into a digital computer. The digital recording system was set at a basic sampling rate of 2500 words per second. After processing, all the data and the calculations performed on the data could be printed out on the control room terminal at 0.1-second intervals.

Injectors

The injectors used in this investigation provided for injection of gaseous-hydrogen fuel through a porous Rigimesh faceplate. The oxidant was injected through 85 showerhead tubes distributed evenly over the injector faceplate. Figure 8(a) shows the faceplate side of an injector. Figure 8(b) is a cross-sectional sketch of one element and shows the liquid-oxygen tube and the porous faceplate through which the fuel was injected.

The injector, the thrust-chamber liner design, and the test procedure, were identical to those used in reference 3 so that the data obtained from the thrust chamber with the fiberglass-wrapped copper closeout could be compared with the tests of more conventional chambers reported in that reference. Further details of the injector design can be obtained from reference 3.

Fiberglass-Wrapped Thrust Chambers with Copper Closeouts

Except for the closeout, the basic design of the thrust chambers was identical to that of the chambers used for the work of reference 3. This was done so that (1) the test hardware would be compatible with the existing test facilities, and (2) a data base would be available for comparing the life of a chamber with a fiberglass-wrapped copper closeout with the life of a chamber with a completely metallic closeout.

The chambers had a contraction ratio of 3.70 and were 38.1 centimeters (15.0 in.) long with the throat located 25.4 centimeters (10.0 in.) from the injector faceplate. The diameters of the throat and nozzle exit were 6.6 centimeters (2.6 in.) and 13.2 centimeters (5.2 in.), respectively. Oxygen-free, high-conductivity (OFHC) copper and annealed Amzirc, which is a 0.15-percent-zirconium copper alloy, were the liner materials.

The chambers were machined from copper billets and had coolant channels milled in the outer surface, as shown in figure 9. (The liner contour shown in this figure is slightly different from the contours of the liners used in this investigation, but the channels in the outer surface have the same dimensions.) After the coolant channels were machined, they were temporarily filled with wax, and a 0.762-millimeter- (0.030-in.-) thick layer of copper was electroformed to the outer surface in order to form a closeout for the coolant channels. The wax was then removed and a low-modulus, high-tensile-strength fiberglass composite was wrapped over the electroformed copper to act as the main structural member for resisting combustion-gas pressure loads during engine firing. Figure 10 is a partial cross-sectional drawing that shows the coolant-channel dimensions and the different material layers. Figure 11 shows a chamber with its fiberglass-wrapped copper closeout and the coolant manifolds welded in place.

A total of five thrust chambers were fabricated. Pertinent details concerning these chambers are as follows:

(1) Chamber 73 was a fiberglass-wrapped chamber with an OFHC copper liner and an 0.762-millimeter- (0.030-in.-) thick electroformed copper coolant-channel closeout. This closeout was applied in two steps. First, 0.762-millimeter- (0.030-in.-) thick copper was electroformed onto the OFHC copper liner, and the electroformed copper was then machined back to a thickness of 0.254 millimeter (0.010 in.). A 0.508-millimeter- (0.020-in.-) thick layer was then electroformed over the 0.254-millimeter- (0.010-in.-) thick layer by reverse plating in order to improve the grain structure of the

closeout. A 0.711-millimeter- (0.029-in.-) thick fiberglass overwrap was next applied in accordance with the following specifications: (1) one layer of E-801 glass hoop filaments (~0.229 mm (0.009 in.) thick), 14 turns per inch, 20 end roving; (2) one layer of 181 glass cloth cut in strips (~0.254 mm (0.010 in.) thick); (3) one layer of E-801 glass hoop filament (~0.229 mm (0.009 in.) thick); and (4) an epoxy resin (wet system) with a 82° to 93° C (180° to 200° F) curing temperature.

(2) Chamber 74 was identical to chamber 73 except that the entire electroformed copper closeout was deposited in two steps by reverse plating and an equivalent fiberglass overwrap was applied by a different contractor. The closeout was applied in two operations in an effort to offset any porous leakage paths that might occur as a result of the electroforming process.

(3) Chamber 75 was identical to chamber 74 except that the fiberglass overwrap was applied by a third contractor who used a textile weaving process. The weave angle was between 0.45 and 0.49 radian (26.0 and 28.0 deg) and resulted in a hoop elastic modulus between 27.6 and 34.5 GN/m^2 (4×10^6 and 5×10^6 psi). Because of geometric constraints imposed by the weaving process, it was necessary to attach the manifolds after the overwrap was cured. The overwrap thickness was approximately 4.572 millimeters (0.180 in.) and resulted in a closeout overwrap stiffness that was approximately five times that of the chamber 74 closeout overwrap.

(4) Chamber 76 was identical to chamber 75 except that the liner was made of annealed Amzirc and the overwrap was 2.54 millimeters (0.100 in.) thick.

(5) Chamber 77 had an Amzirc liner and a fiberglass overwrap that was applied identically to that of chamber 74.

Instrumentation

Thrust-chamber instrumentation consisted primarily of thermocouples. One copper-constantan alloy thermocouple was bonded onto the outside diameter of the combustion chamber to monitor the overwrap temperature during the firing cycle. Each of four high-response Chromel-constantan thermocouples was placed inside a 0.35-millimeter- (0.014-in.-) diameter stainless-steel sheath and was spring loaded against the bottom of a hole drilled into a rib of the liner (fig. 10). The four thermocouples were located 90° apart at the throat plane of the thrust chamber. Their distances from the inside diameter of the thrust chamber varied from 0.737 millimeter (0.029 in.) to 1.600 millimeter (0.063 in.) from the inside diameter of the thrust chamber. As reported in reference 3, a gaseous-helium flow was used to displace condensible gases from the entrances of the thermocouple holes.

TEST PROCEDURES

The test procedure selected was identical to that used in reference 3. The total test-cycle duration was approximately 2.3 seconds, with 0.80 second at rated thrust. The heating transient was 0.05 to 0.06 second and the cooling transient was 1.4 seconds. The liquid-hydrogen coolant flow was continuous at a flow rate of 0.91 kg/sec (2.0 lbm/sec) during the entire cycle so that the chamber would be cooled to the original condition after firing. A schematic of the test cycle is shown in figure 12. Enough liquid-hydrogen storage capacity was available for 125 cycles in a single firing series.

The test cycles were programmed into a solid-state timer that was accurate and repeatable to within ±0.001 second. Fuel and oxidizer flows were controlled by fixed-position valves and propellant tank pressures. Coolant flow was controlled by a cavitating venturi. Coolant inlet pressure was controlled by coolant tank pressure, and coolant exit pressure was kept constant by a closed-loop controller modulating a backpressure valve. Control room operation of the test included monitoring of the test hardware by means of three closed-circuit television cameras and one cell microphone. The outputs of the microphone and one television camera were recorded on magnetic tape for later playback. The cell microphone was the primary data sensor for determining the time of the fatigue failure. During the cooling transient, between thrust pulses while the coolant continued flowing, any coolant leakage significant enough to indicate a throughcrack in the wall between a coolant channel and the combustion chamber could be heard very clearly.

RESULTS AND DISCUSSION

Post-Test Thermal Analysis

The objective of this program was to determine if a less stiff fiberglass-wrapped copper closeout would improve the cyclic life of a thrust chamber over that obtained with a stiffer completely nickel closeout. To accomplish this objective, we had to determine if the hot-gas-side surface temperature was the same for both test specimens. Therefore, since the hot-gas-side surface temperature could not be measured directly, we had to calculate this temperature from measured rib temperatures in conjunction with a thermal analysis. The following procedure was used: (1) the measured rib temperatures were plotted as a function of time; (2) a thermal model of the chamber cross-section was developed; (3) the boundary conditions needed for the conduction analysis were calculated; and (4) an iterative two-dimensional conduction analysis using the SINDA thermal analyzer program was performed until a best match of the theoretical and

measured rib temperatures was achieved. Once this was accomplished, the theoretical hot-gas-side surface temperature was determined from the resulting thermal map.

Because of the large amount of data obtained in the experimental testing, a detailed analysis of the data from every cycle was not possible. Therefore, random samples of the recorded data were analyzed to determine if the test parameters remained essentially constant throughout the life of the chamber. Analysis of the data showed this to be true once the desired cycle was established. It was concluded then that any cycle throughout the chamber life was representative of a "nominal" cycle.

Figure 13 shows the experimental rib-temperature data at the throat plane and the calculated matching curves. The calculated temperature curves match well with the experimental data. Also shown are the thermal model used in the conduction analysis and the relative depth locations of the two thermocouples used for the experimental temperature data. (The other two thermocouples were inoperative.) The thermocouples were located 0.099 and 0.160 centimeter (0.039 and 0.063 in.) from the hot-gas-side surface and at the rib centerline. The model is identical to the one that was used for the preliminary analysis. Although the SINDA program is capable of performing a three-dimensional thermal analysis, only a two-dimensional analysis was used. The program outputs the temperature for each nodal point in the model; however, only the matching curves for the two thermocouples are shown.

The theoretical hot-gas-side wall temperature of a fiberglass-wrapped thrust chamber is compared with that of a thrust chamber with only an electroformed nickel closeout in figure 14. The curve for the chamber with the nickel closeout was duplicated from reference 3, which reports the cyclic lives of several thrust chambers with OFHC copper liners and electroformed nickel closeouts. This curve was also generated from experimental rib-temperature data in conjunction with a thermal analysis. The hot-gas-side surface temperatures were nearly the same throughout the cycle. Therefore it was concluded that a comparison of the lives of these two types of chambers would be valid.

Test Results

Before cyclic life testing, each chamber was hydrotested to assure structural integrity. The pressures during the hydrotest were 8.27 MN/m^2 (1200 psi) in the coolant channels and 6.20 MN/m^2 (900 psi) in the combustion chamber. Two of the chambers, 73 and 77, developed a crack in the thin, electroformed copper closeout during the hydrotest and thus could not be cyclically tested. These failures were believed to be a result of a poor-quality closeout.

Chamber 74, which had an OFHC copper liner and a fiberglass-wrapped copper closeout, was cyclically test fired 192 times before it failed because of crack in the coolant-channel wall near the throat, as shown in figure 15. Chamber 75, which was

identical to chamber 74 except that its closeout overwrap stiffness was approximately five times greater, failed because of a crack in the coolant-channel wall near the throat at 199 cycles, as shown in figure 16. The appearance of these cracks is identical and they are typical of the throat region cracks that occurred in similar chambers, as reported in reference 3. The coolant channels adjacent to the failed channel changed from their original rectangular shape; this indicates that plastic deformation was occurring in the channel walls. Both OFHC copper chambers developed premature leaks through the electroformed closeout before the coolant-channel wall failed. However, the leakage was not severe enough to require termination of cyclic testing, and it did not occur in the same channel in which the crack eventually occurred.

The location of the crack in the outside surface of the closeout on chamber 75, after the fiberglass overwrap was removed, is shown in figure 17. A section through the coolant channels near the crack is shown in figure 18. There were two distinct layers of electroformed copper as a result of the two-step electroforming process mentioned earlier. There was a small crack in the inner layer (fig. 18). A section through the closeout at the same circumferential location but approximately 5.84 millimeters (0.230 in.) downstream from the section in figure 18 is shown in figure 19. Here the outer layer was quite porous. The combination of these two defects could account for the hydrogen leakage in this channel.

The average cyclic life of four chambers with liners identical to those of chambers 74 and 75 and with completely nickel closeouts is reported in reference 3 as 150 cycles (130- to 165-cycle range). The average life of chambers 74 and 75 was 195 cycles. From these results, it appears that the fiberglass-wrapped copper closeout increased the chamber life by approximately 30 percent, which is the amount of improvement predicted by the preliminary analysis (25 to 30 percent).

The overwrap stiffnesses of chambers 74 and 75 were believed to be approximately 26.7×10^6 and 142×10^6 N/m (0.15×10^6 and 0.81×10^6 lbf/in), respectively. Even though the overwrap stiffnesses were considerably different, the cyclic lives of these two chambers were approximately the same (192 and 199 cycles). A possible explanation is that the closeout was not in contact with the fiberglass overwrap in the throat region during the heating and cooling transients. As a result, the fiberglass overwrap would have had no effect on the thermal strain (and consequent life) of the liner in this region. If it is assumed that the closeout was not in contact with the fiberglass overwrap, the liners of both chambers would theoretically experience the same strain during the heating and cooling transients and hence would have the same lives.

The theoretical life in the throat region for a chamber with a 0.762-millimeter- (0.030-in.-) thick metallic closeout and no overwrap (stiffness equal to zero) is approximately 200 cycles based on the average strain range (fig. 6). Comparing this value with the actual lives of 192 and 199 cycles for chambers 74 and 75, respectively, suggests that the closeouts of these chambers may not have been in contact with their fiberglass

overwraps. Consequently, it may be concluded that life was improved by a reduction in closeout stiffness in the throat region and that the stiffness reduction was due to the replacement of the stiff nickel closeout with a less stiff, thin copper closeout that had no support from the fiberglass overwrap. Because of the small chamber diameter and the narrow coolant channels in the throat region, the liner and its closeout could support the pressure loads without the aid of the fiberglass overwrap. In the combustion-chamber area, however, where the chamber diameter was larger and the coolant channels were wider, the fiberglass overwrap was required to support the loads. Even though the fiberglass overwrap was not required to carry the pressure loads in the throat region for the particular thrust chambers tested, it would probably be required to support thrust and gimbal loads in a practical thrust chamber unless a separate load-carrying structure was provided.

Chamber 76, which was identical to chamber 75 except that the liner material was annealed Amzirc and the fiberglass overwrap was 2.54 millimeters (0.10 in.) thick, was cyclically tested for 256 cycles. Testing was terminated at this time because cracks in the electroformed copper closeout became a safety hazard, and not because of a crack in in the coolant-channel wall. Figure 20 shows a cross-sectional view of the throat plane at 256 cycles. Very little coolant-wall deformation and thinning can be observed; thus considerably more cycles might have been endured by the liner if the closeout had not failed. Figure 21 shows the locations of the two closeout-cracks after the overwrap was removed. Both were in areas where the chamber diameters were larger than the throat diameter. Figure 22 shows the closeout crack that occurred farthest from the throat.

If it was assumed that the fiberglass overwrap was not in contact with the liner during the cooldown period, the bending stress in the electroformed copper at the corners of the coolant channel was approximately 94.6 MN/m^2 (13 720 psi), with a coolant pressure of 6.895 MN/m^2 (1000 psi). The coolant-channel corners ajacent to the closeout were rather sharp, as shown in figure 23. Therefore, if we assume a stress concentration factor of 2.0, the bending stress at the corners could be as high as 189 MN/m^2 (27 440 psi). The yield stress of electroformed copper at 27.8 K (50° R) is approximately 145 MN/m^2 (21 000 psi) (ref. 7), so the corner stresses could have been beyond the yield stress. Based on this, it is conceivable that the liner closeout developed a crack early in the cyclic test and that the crack propagated through the closeout as the test progressed. This theory is enhanced by the fact that the strength of electroformed copper depends on the quality of the application process and that flaws are more critical in thin layers such as the closeout.

The maximum cyclic life of the Amzirc chamber tested under the same conditions and reported in reference 3 was 63 cycles. Hence, it appears that in this case the thin copper closeout with a fiberglass overwrap had a significant effect in prolonging chamber life. However, since Amzirc is an alloy, there may have been enough difference in the

liner materials to account for some of the improved cyclic life. Reference 3 attributes the short life of the Amzirc chambers to the uneven distribution of zirconium, although its concentration was as specified.

CONCLUDING REMARKS

Although the results of this investigation are very limited, they did indicate that reducing the stiffness of the usual stiff metallic closeout can improve thrust chamber liner life. However, the problem of cracks in the thin closeout must be eliminated before fiberglass-wrapped closeouts can be regarded as an acceptable substitute for metallic closeouts. If a fiberglass overwrap is used, it is necessary to provide an electroformed metallic closeout over the milled coolant channels. The closeout should be as thin as possible in order to realize the benefits of the low-elastic modulus fiberglass overwrap. However, any flaws or irregularities in a thin electroformed material become critical. Therefore an effort should be made to improve the quality of the closeout, or perhaps other methods of sealing should be investigated. One possible improvement would be to eliminate the sharp corners at the junctions of the electroformed closeout and the coolant-channel ribs. Also, the fiberglass overwrap should be applied in a manner that produces a prestress in the liner and the overwrap in order to ensure that the overwrap carries its share of the hoop load in the combustion chamber area.

SUMMARY OF RESULTS

Three of five rocket thrust chambers with copper liners were cyclically test fired to failure. The remaining two chambers developed cracks in the closeout seal during hydrotesting. The combustion-chamber pressure was 4.14 MN/m^2 (600 psia) and the oxidant-fuel ratio of the liquid-oxygen and gaseous-hydrogen propellants was 6.0. Two of the cyclically test-fired liners were made from oxygen-free, high-conductivity (OFHC) copper and one from annealed Amzirc. The liners were fabricated in the shape of a typical thrust chamber and had externally milled coolant channels. The coolant channels were closed out by a electroforming a 0.76-millimeter- (0.30-in.-) thick copper shell over the channels to prevent leakage of the liquid-hydrogen coolant. A fiberglass composite was applied over the closeout to provide hoop strength for resisting the combustion gas pressure. The following results were obtained:

1. The average lives of the two OFHC copper liners with fiber-glass-wrapped copper closeouts were approximately 30 percent longer than the average life of four equivalent chambers with stiffer nickel closeouts tested under the same conditions.

2. After 256 cycles, the chamber with the Amzirc liner and fiber-glass-wrapped copper closeout had no hot-gas-side coolant wall cracks even though this was approximately four times the number of cycles to failure for a similar liner with a stiffer nickel closeout. It was necessary to terminate the testing after 256 cycles because sufficient liquid hydrogen was leaking into the test area through cracks in the electroformed copper closeout to create an unsafe condition.

3. The 0.76-millimeter- (0.030-in.-) thick electroformed copper closeout may be too thin to compensate for any flaws or irregularities in the copper.

4. Thin copper closeouts with fiberglass overwraps were less constrictive to liner thermal deformation and hence improved liner cyclic life.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 6, 1979,
506-21.

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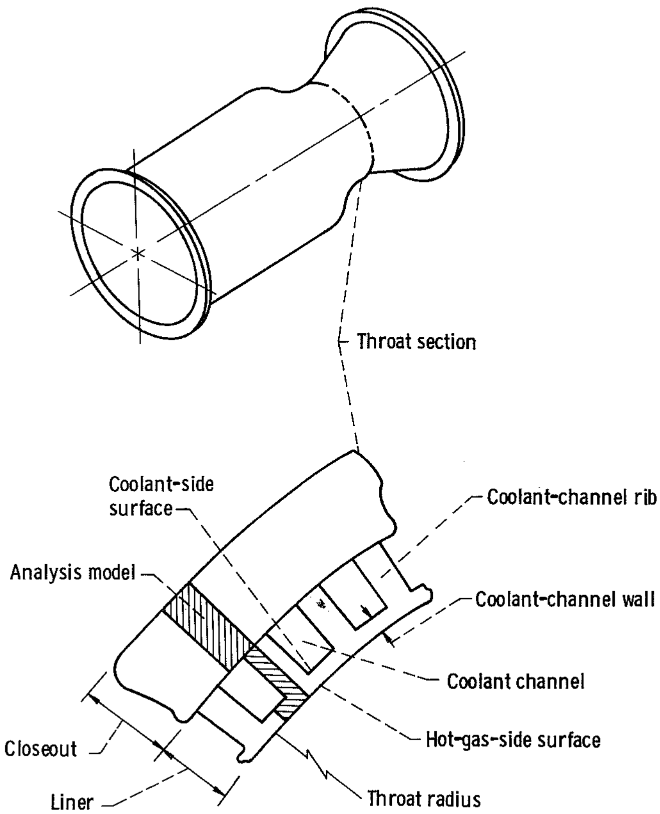


Figure 1. - Typical regeneratively cooled, milled-channel thrust chamber.

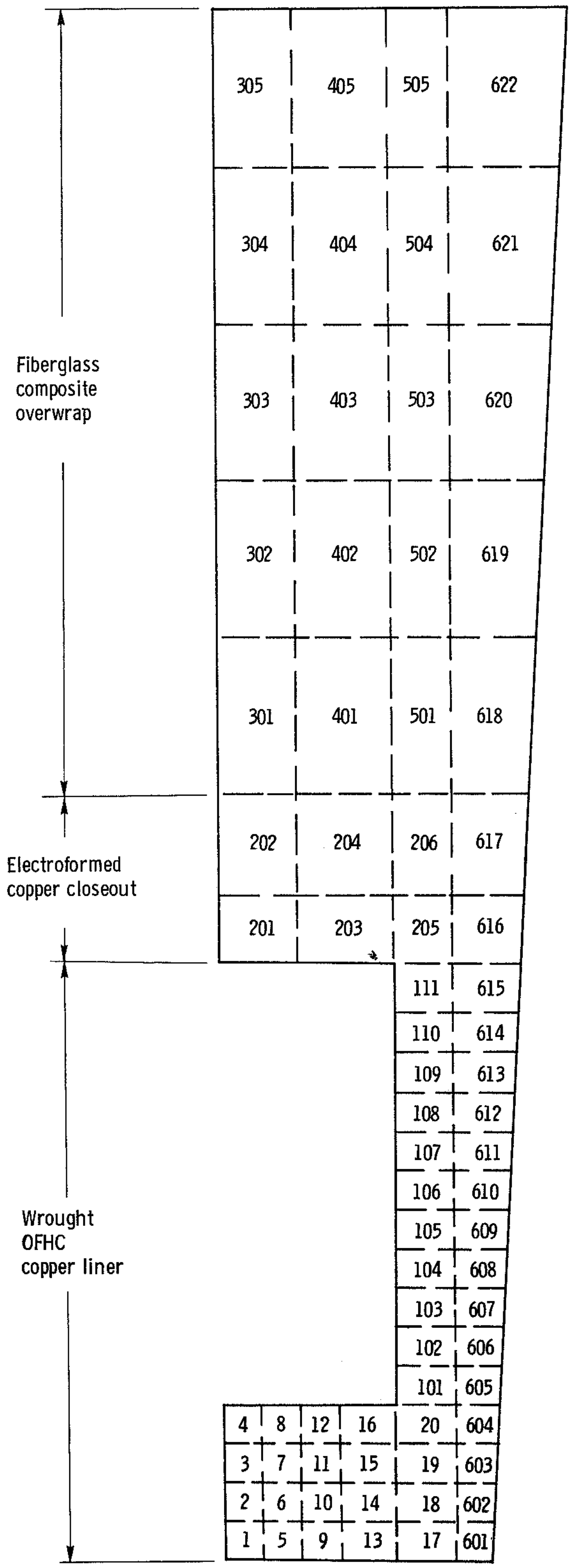


Figure 2. - Thermal analysis model.

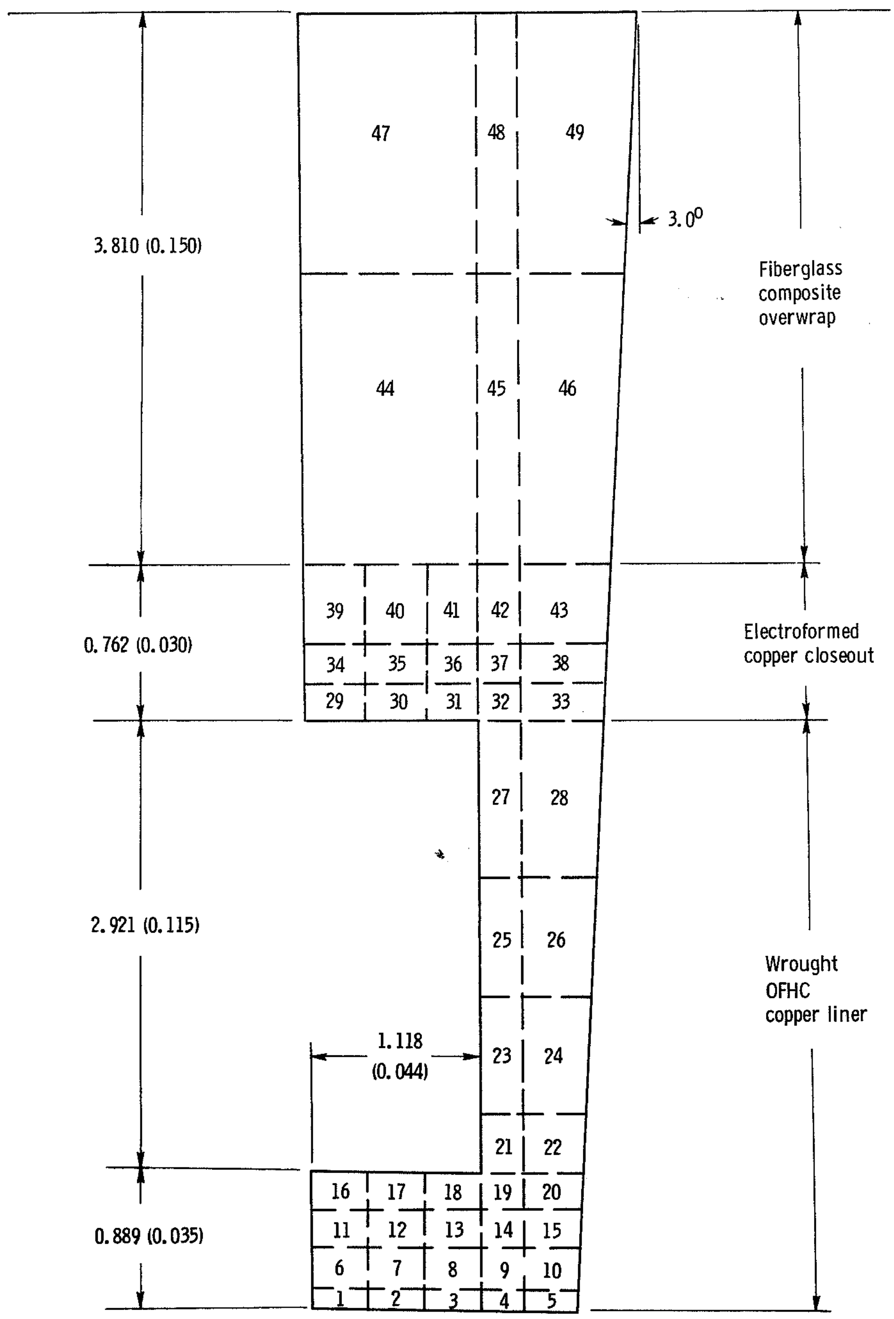


Figure 3. - RETSCP finite-element model. (Linear dimensions are in mm (in.).)

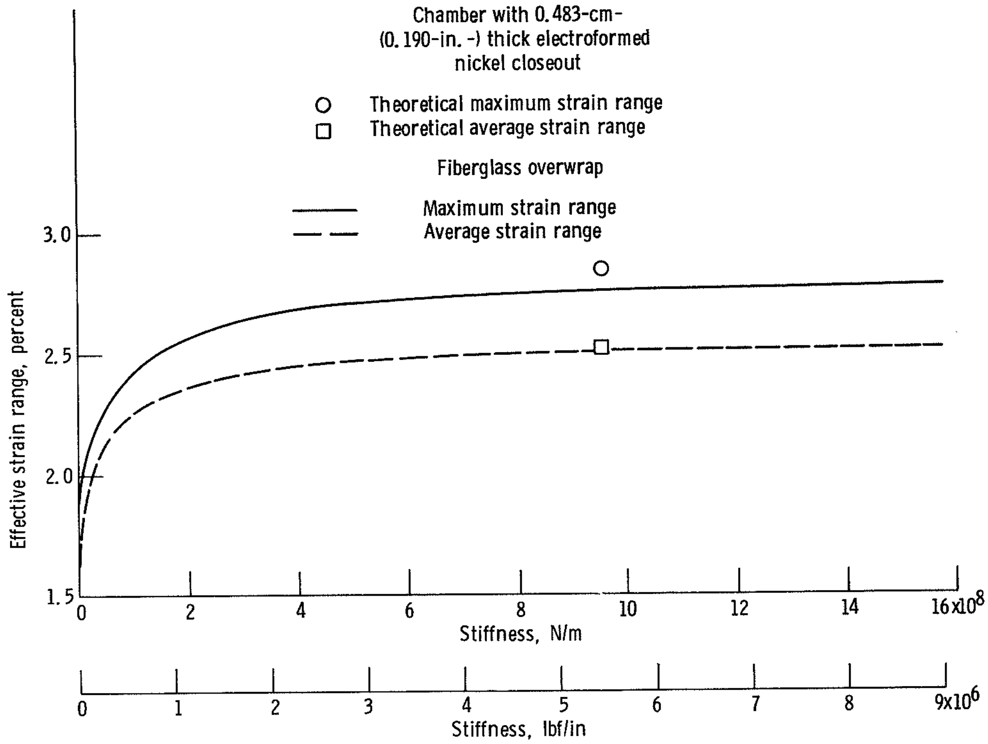


Figure 4. - Effect of fiberglass-overwrap stiffness on liner cyclic strain range. Overwrap thermal coefficient of expansion, 5.04×10^{-6} cm/cm·°C (2.8×10^{-6} in/in·°F); Stiffness = Modulus of elasticity x Overwrap thickness.

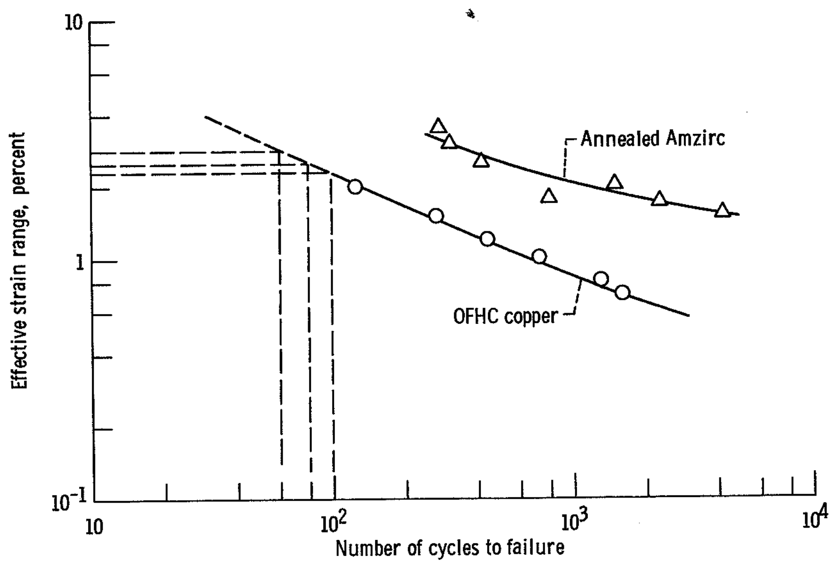


Figure 5. - Typical low-cycle fatigue life of annealed OFHC copper and annealed Amzirc. Strain rate, 0.002 sec^{-1}; temperature, 811 K (1460° R). (From ref. 8.)

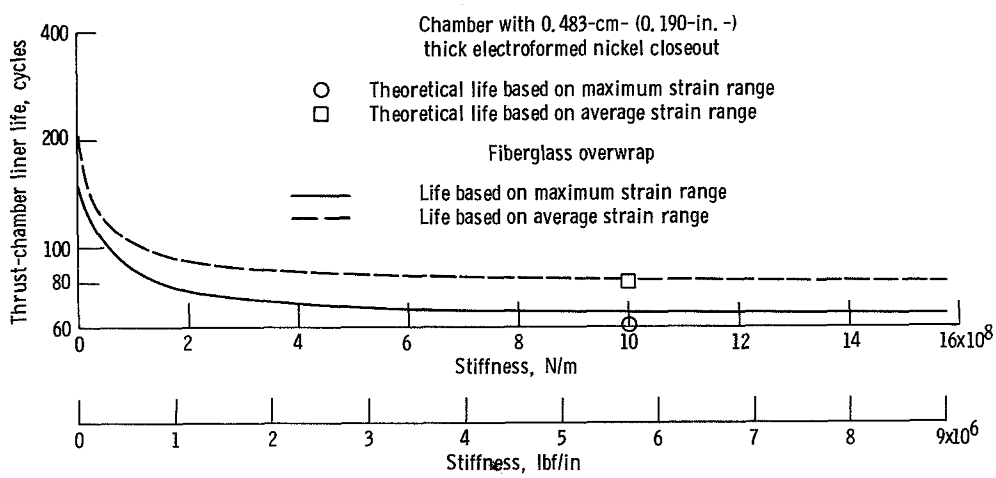
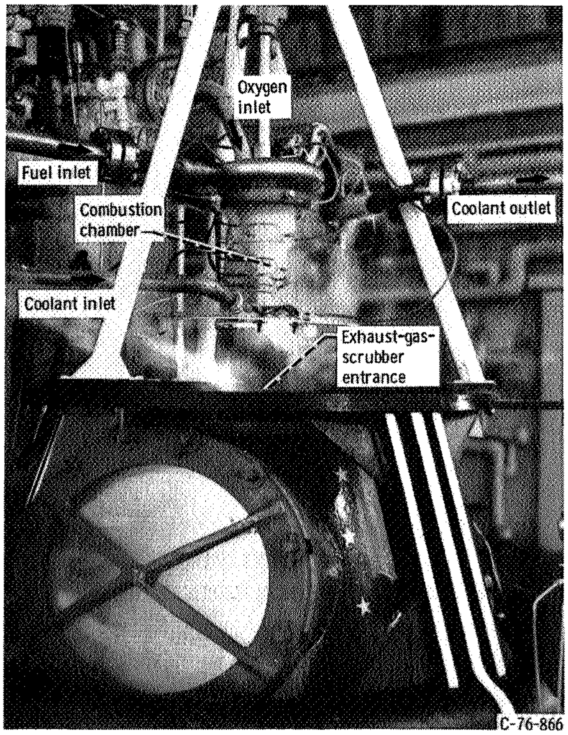
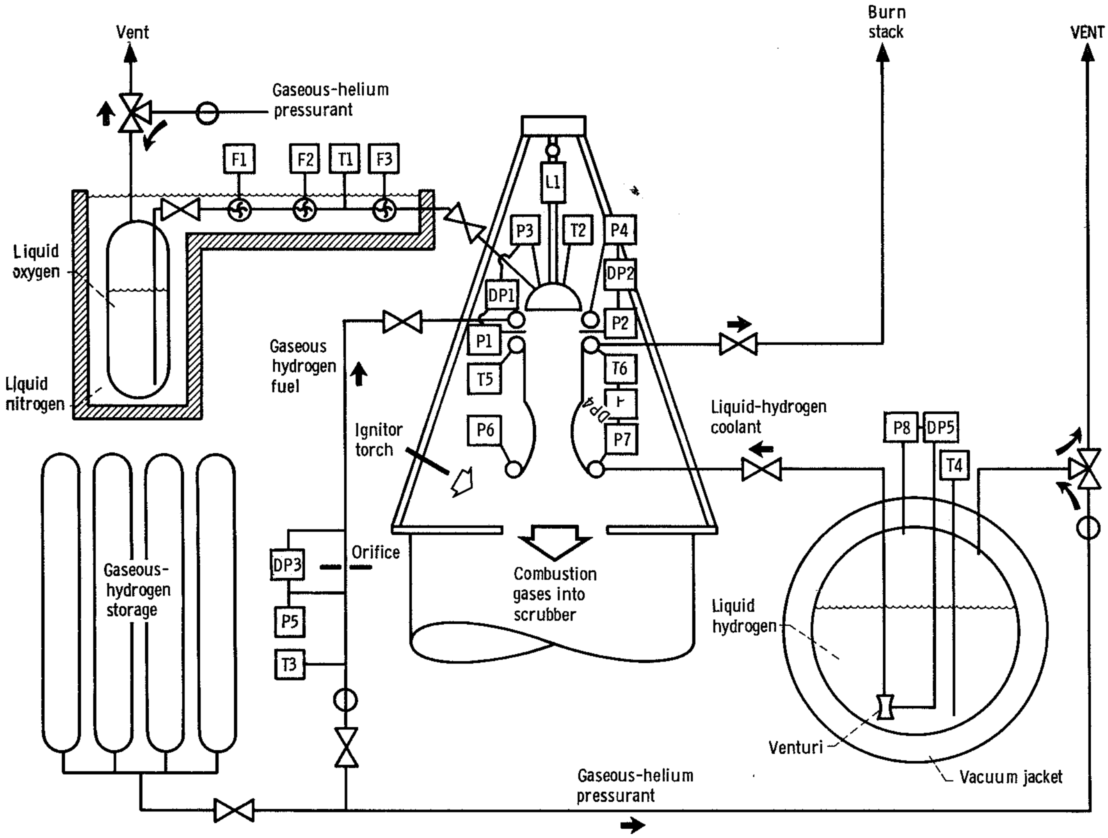


Figure 6. - Effect of fiberglass-overwrap stiffness on thrust-chamber liner life. Overwrap thermal coefficient of expansion, 5.04×10^{-6} cm/cm · °C (2.8×10^{-6} in/in · °F); Stiffness = Modulus of elasticity x Overwrap thickness.

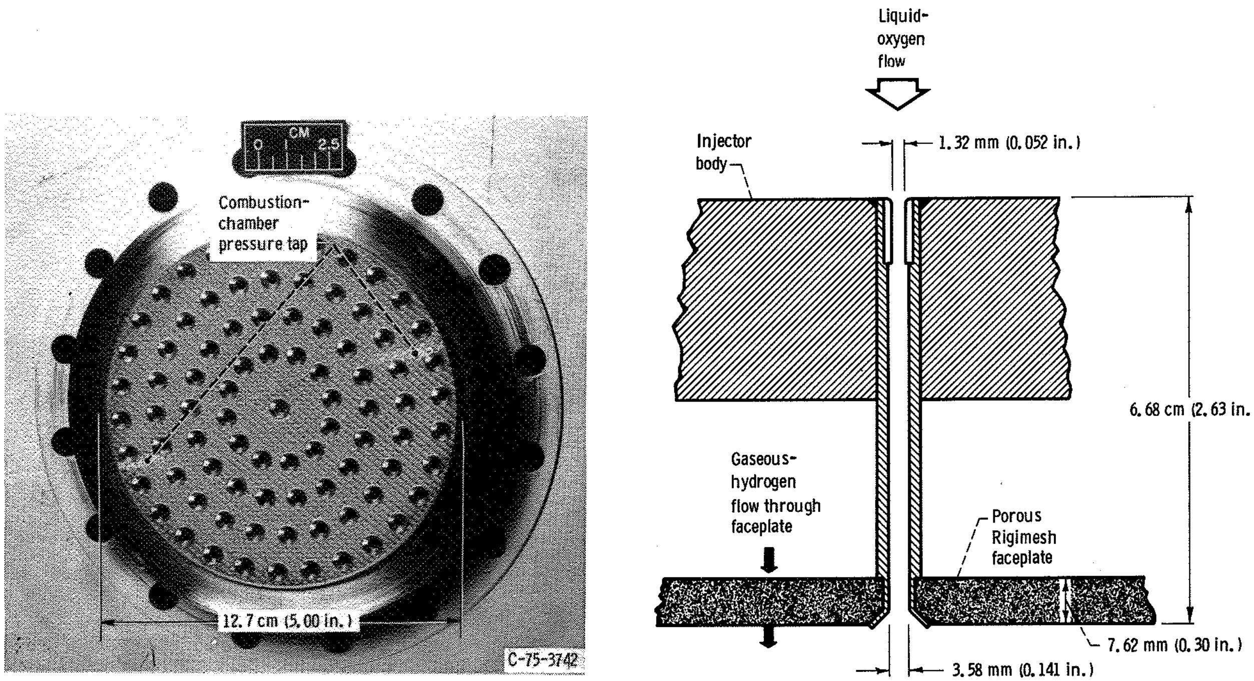


(a) Test combustion chamber and thrust stand.



(b) Schematic of test facility.

Figure 7. - Test facility.



(a) Injector faceplate.

(b) Sketch of injector element.

Figure 8. - Injector.

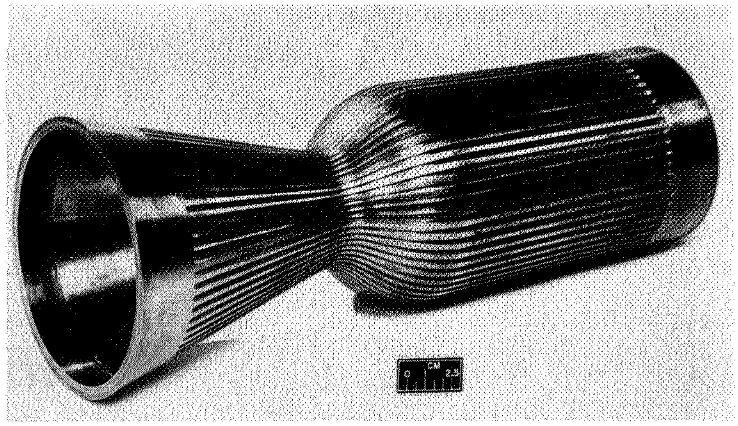


Figure 9. - Typical thrust-chamber liner.

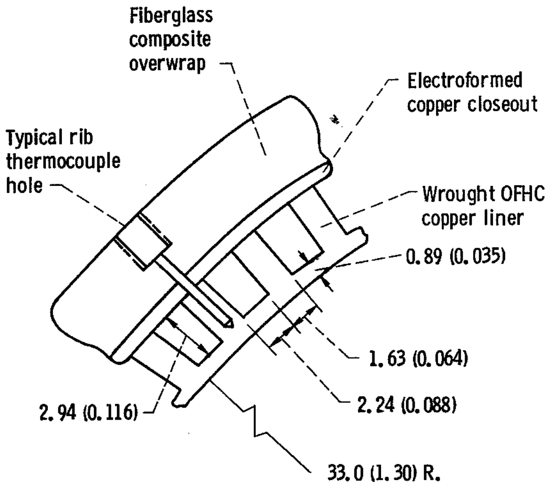


Figure 10. - Partial cross section of throat. (Linear dimensions are in mm (in.).)

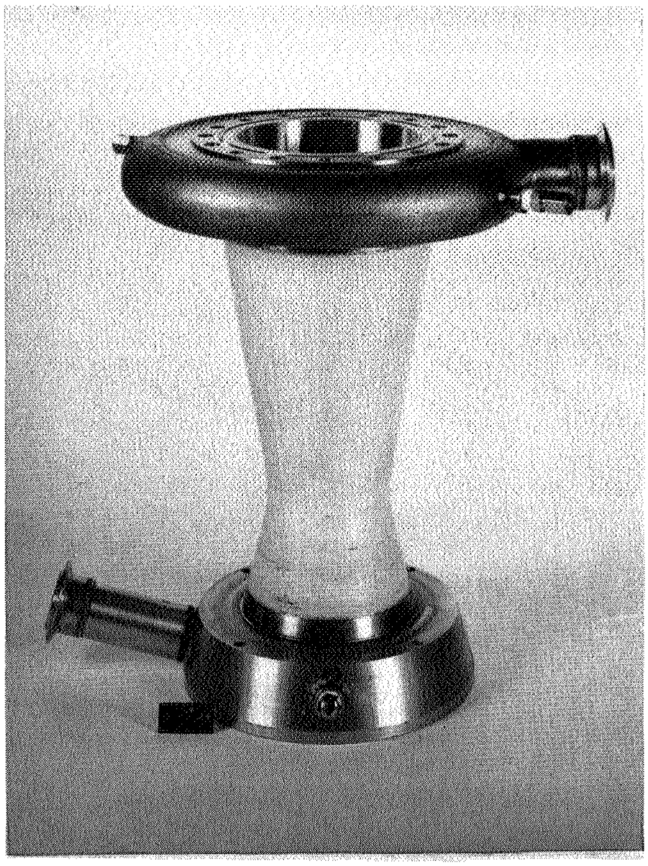


Figure 11. - Typical thrust chamber with fiberglass-wrapped copper closeout.

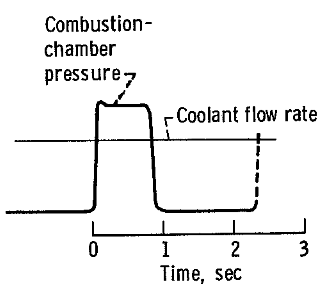


Figure 12. - Schematic of cycle used in fatigue testing of rocket chambers.

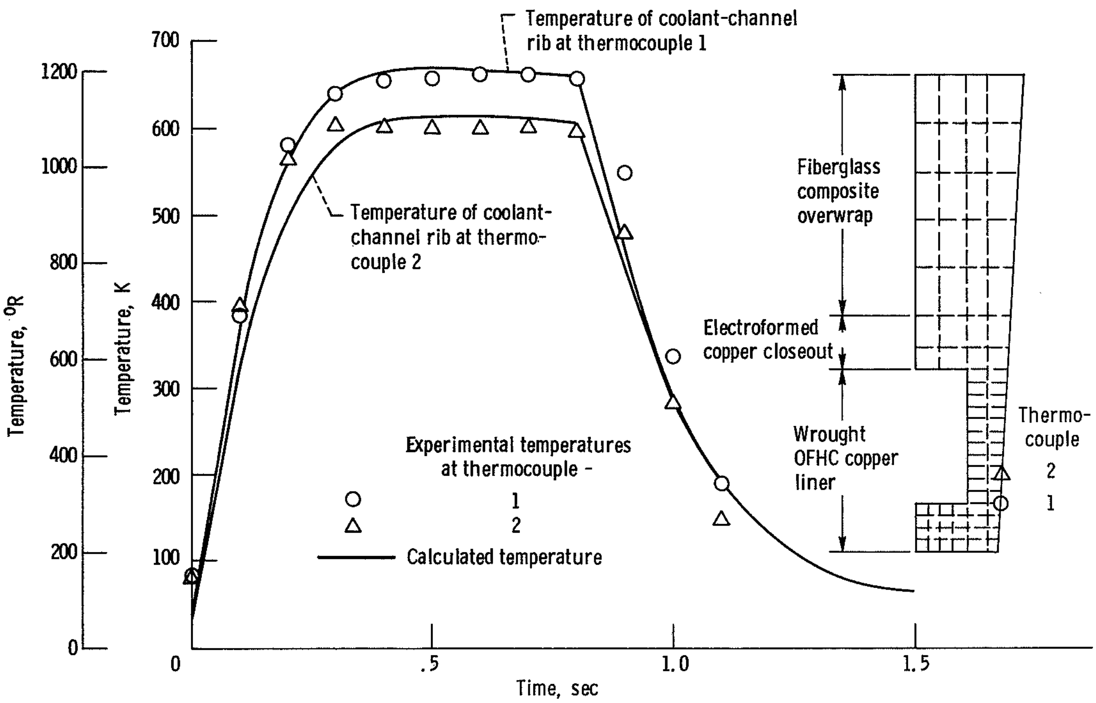


Figure 13. - Matching of thermal analysis with experimental data.

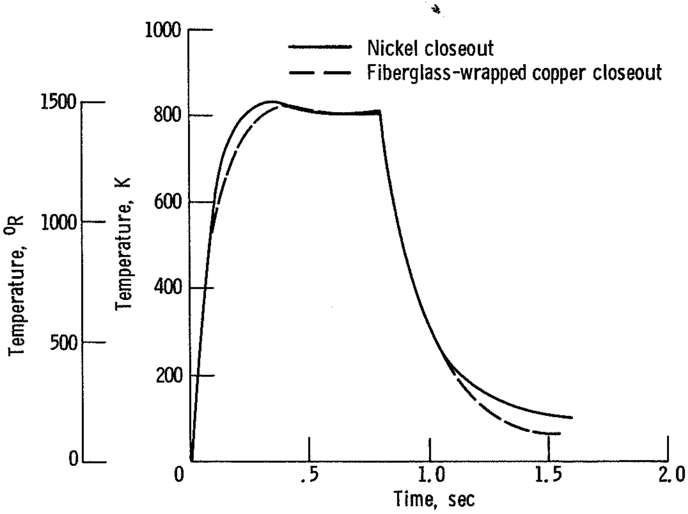


Figure 14. - Comparison of theoretical hot-gas-side surface temperatures at rib centerline for a thrust chamber with a completely nickel closeout and one with a copper closeout wrapped with fiberglass.

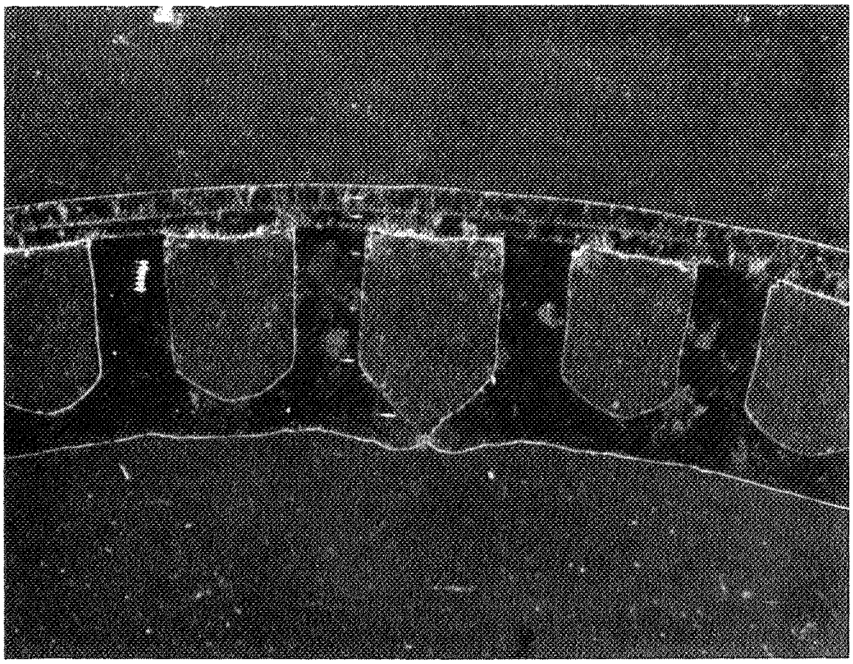


Figure 15. - Crack in coolant-channel wall of chamber 74. X7.

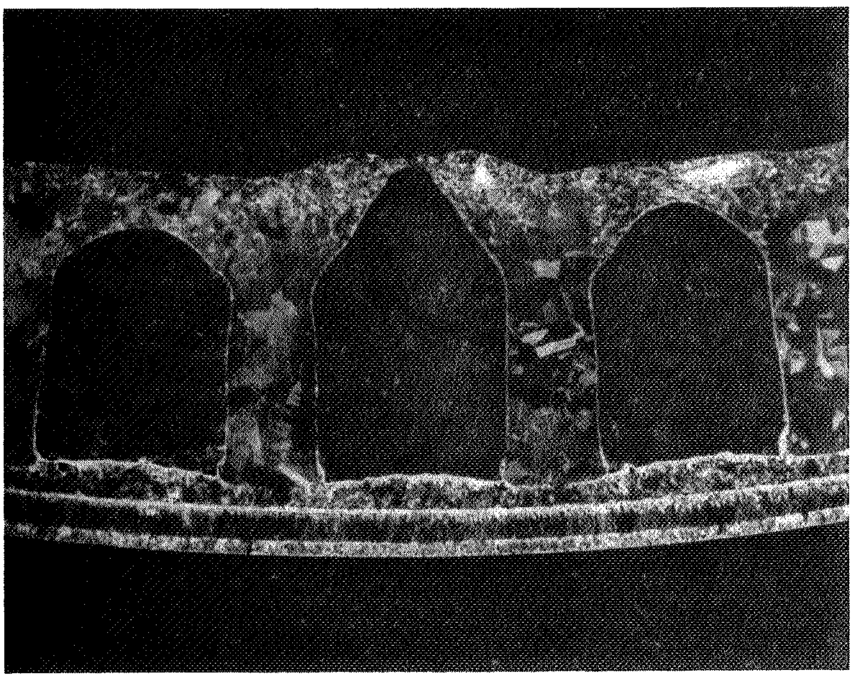


Figure 16. - Crack in coolant-channel wall of chamber 75. X10.

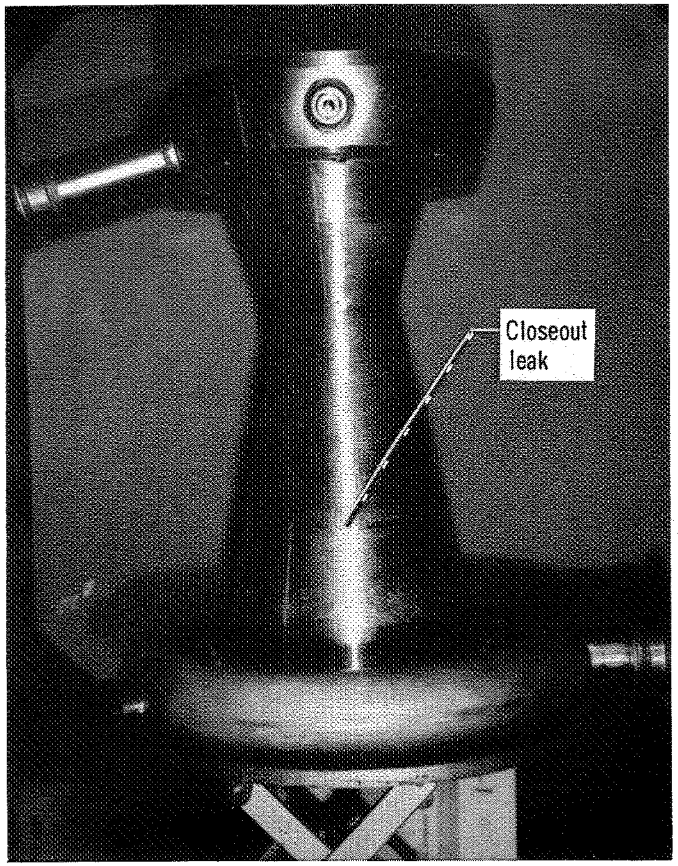


Figure 17. - Location of leak in chamber 75.

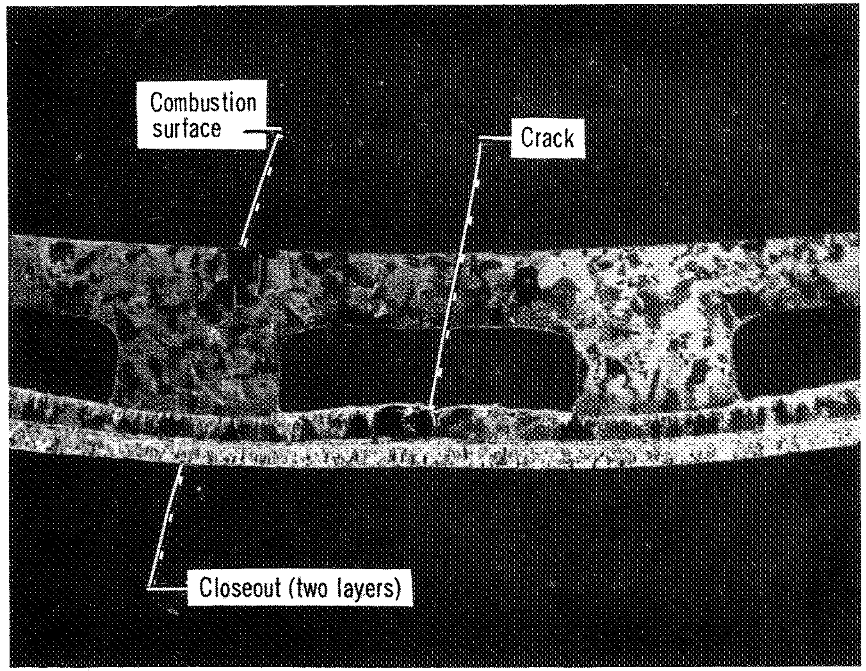


Figure 18. - Crack in inner electroformed layer of chamber 75 closeout. X10.

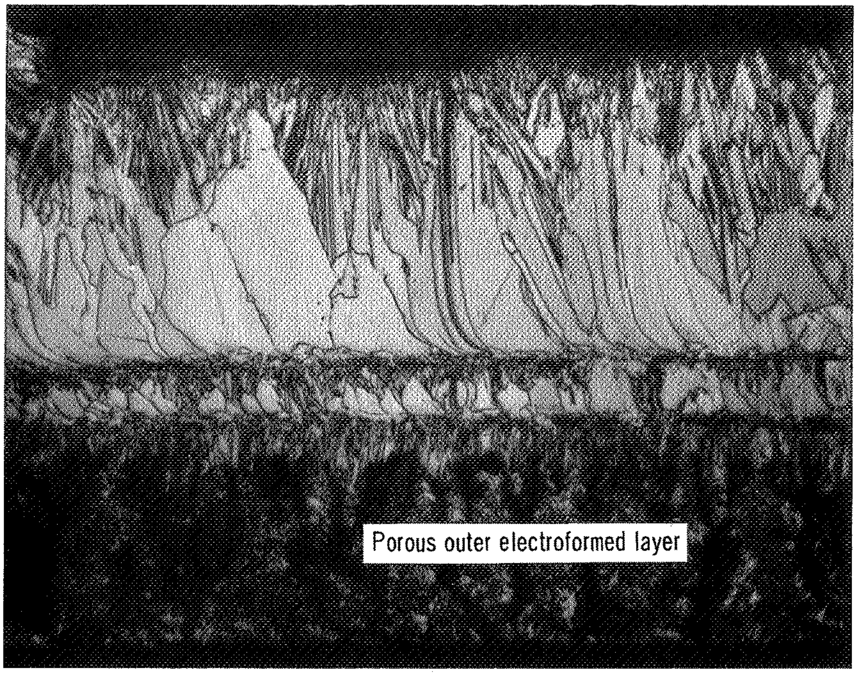


Figure 19. - Porous outer electroformed layer of chamber 75 closeout. X100.

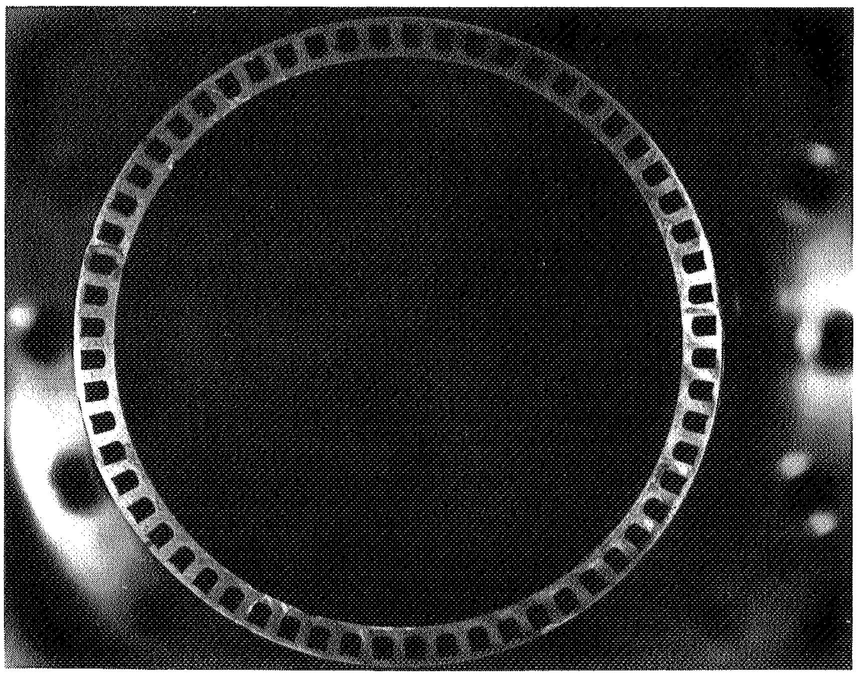


Figure 20. - Throat plane section of chamber 76 after 256 cycles.

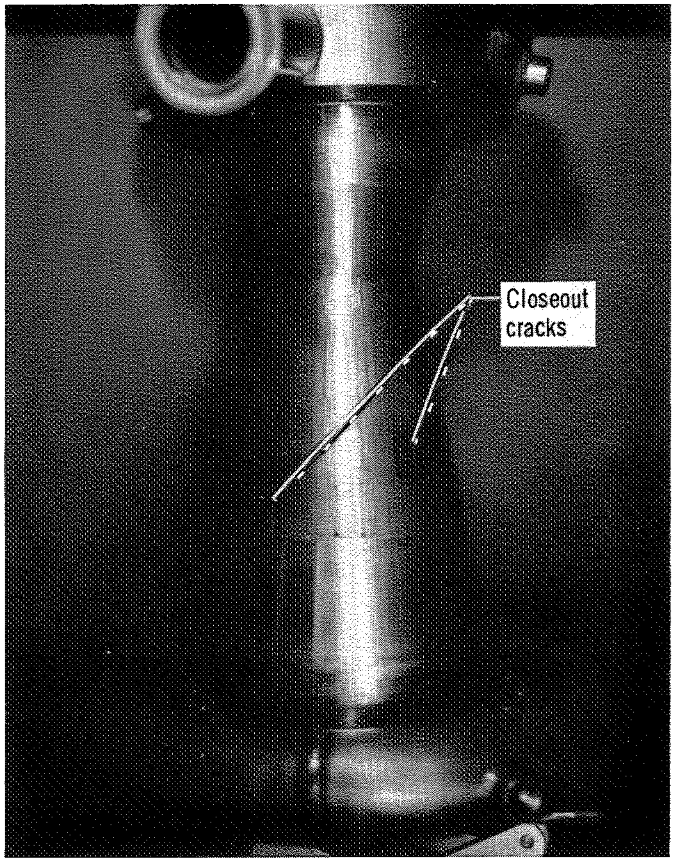


Figure 21. - Locations of cracks in chamber 76 closeout.

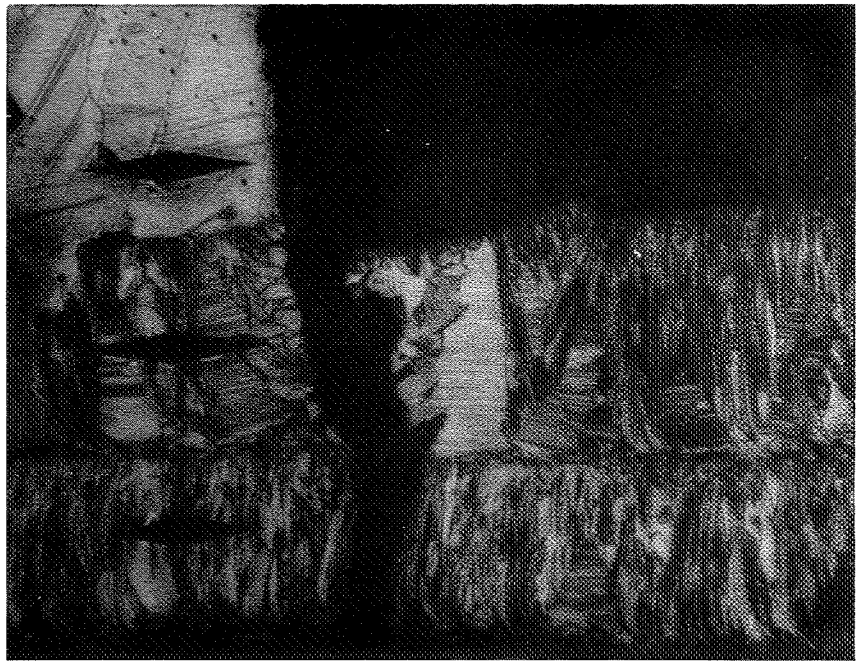


Figure 22. - Crack in chamber 76 closeout. X100.

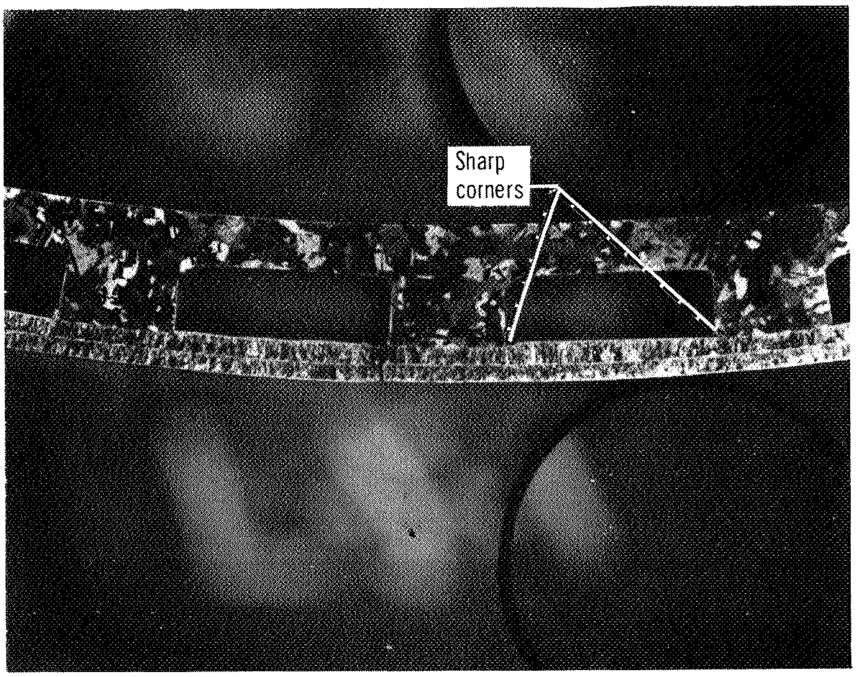


Figure 23. - Section showing sharp corners of coolant channels adjacent to chamber 76 closeout. X7.

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15. Supplementary Notes

16. Abstract

Three rocket thrust chambers with copper liners and a thrust level of 20.9 kN (4700 lbf) were cyclically test fired to failure. Two of the liners were made from oxygen-free, high-conductivity (OFHC) copper and one from annealed Amzirc. The milled coolant channels were closed out with a thin copper closeout over which a fiberglass composite was wrapped to provide hoop strength only. Experimental data are presented, along with the results of a preliminary analysis that was performed before fabrication to evaluate the life-extending potential of a thin copper closeout with a fiberglass overwrap.

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